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# ADVANCES IN FREIGHT TRANSPORT DEMAND MODELLING: AN ASSESSMENT WITH RESEARCH PERSPECTIVES

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## Abstract

For a long time, freight transport demand models have been adapted from those for passenger demand. However, in recent years, specific methods have been developed to address specific issues pertaining to freight, including: the formation of scale economies; the integration of logistic stages along the transport chain of a shipment; the spatial and technical structure of the industry and the requirements for trade.

The paper is purported first to review freight models that bring about such advances; second, to assess the advances with respect to the representation of demand, supply, market, regulation, and sector activity. A typology framework is put forward to classify the advanced models, and some research topics are identified.

## Keywords

Freight, logistics, transport demand, choice behavior, shipment, spatialized input-output, methodology, modeling.

## 1. INTRODUCTION.

### 1.1 Issues.

From a political point of view, freight transport is a complicated sector of the economy to tackle with. It is indeed closely interdependent with both the whole of industry, which requires goods to be taken from places to others under a set of tight constraints, and people's everyday life, their need for transport capacity, and their reluctance to bear the negative impacts of freight traffic. This sector is also subject to a number of market distortions and externalities (most notably, scale economies, congestion and environmental impacts), which implies that the market has little chance to reach a socially optimal situation in its own – meaning that regulation is in order. Such a regulation is all the more efficient as it is backed by a thorough understanding of, first, the operation of the freight transport sector; second, the potential influence of a range of regulation policies. Freight transport modelling is aimed to contribute to that understanding, by providing firstly a systemic or economic representation of the freight transport sector, secondly tools to estimate and forecast quantitative indicators of its activity.

The methods applied in the field of freight transport modelling have been, up to recent times, largely inspired from those designed for and used in passenger transport modelling. This is particularly true with respect to the models architectures and the underlying economic and behavioural hypotheses. Their adaptation to the

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particularities of freight transport has thus been deemed necessary, and has been undertaken by several research teams throughout the world.

Several works recently published proceed from this adaptation effort. This paper is purported to highlight the recent achievements and also to identify some under-addressed issues. This is not our objective to review all existing methodologies and model architectures, but rather to present some of the works which have either emphasized a particular characteristic of the freight transport sector, or designed an element of methodology addressing a problem specific to the modelling of freight transport, supply and demand.

## 1.2 Objectives and Method.

This paper proceeds in three stages, addressing in turn the three following objectives: first, the presentation of some recent, advanced freight transport demand models; then, the analysis and logical organisation of these advanced models; lastly, the identification of some fields that remain to be investigated.

Our review is focused mainly on spatialised freight transport models. We shall consider the model for freight concentration and intermodal transport designed by B. Groothedde (2003), the strategic railway simulation model in NEMO and its interaction with the microscopic simulation model RailSys, the NODUS model, the simulation models designed in the frame of the European projects EUNET2.0 and SCENES, the urban freight transport model FRETURB, the ECHO French shipment survey, and finally the REDEFINE European project. Each model will be described in terms of principles and behavioural assumptions and of logical architecture, before we focus on its innovation. We will also compare the methodological choices to the claimed objectives.

This review is focused on issues specific to the modelling of freight transport demand. Thus, we shall assess the modelling developments with respect to a set of issues which we believe specific to both the understanding and the modelling of freight transport:

- The representation of demand in terms of volume, behaviour and agent heterogeneity.
- The representation of supply in terms of networks and layers, transport and logistic features, macroscopic relationships including scale economies and congestion effects.
- Relationships between agents and external impacts.
- Policy assessment.

We shall establish a typology to identify and classify the advances, distinguishing both the approach and the scope of the modelling. The typology allows us to suggest potential linkages between the models under review. Our conclusion is devoted to the identification of some under-investigated issues.

## 2. A REVIEW OF ADVANCED MODELS.

A number of works were selected from a large set of recent contributions, on the basis of their innovative characteristics in the field of freight transport modelling. Although they vary widely in both scope and approach, we chose to bring together those works which concern similar subjects.

## 2.1 Refined modelling of service supply in railway transport.

The representation of costs, and particularly of congestion costs (or, equivalently, of capacity limitations) is often over-simplified. This is particularly true with respect to the non-road modes, of which the operating processes make it difficult to model the capacities. We present here a strategy designed to provide an accurate representation of supply costs in railway transport, within a framework which also considers passenger transport.

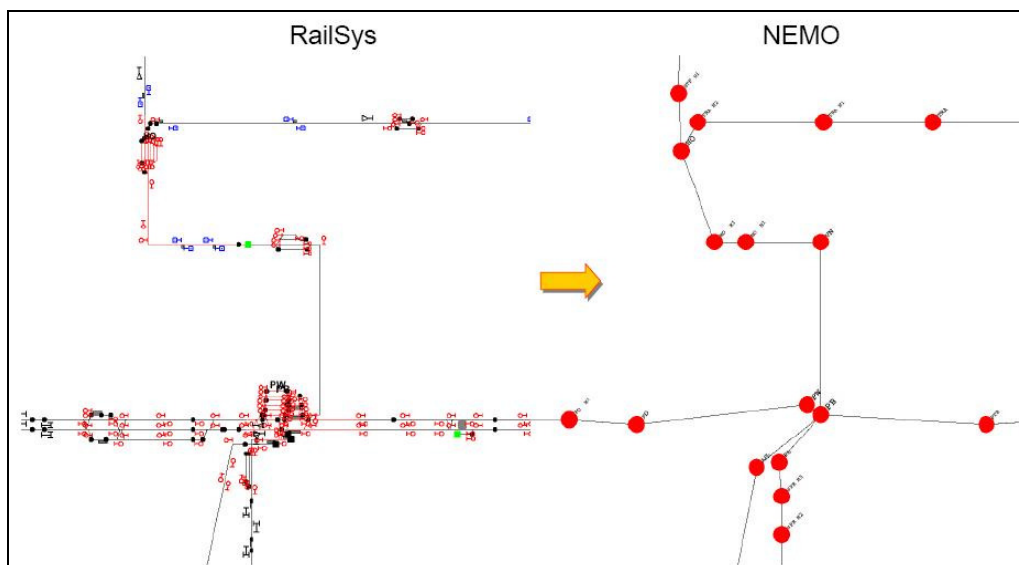
The Institute for Building and Operating Railway of the University of Hannover has developed an architecture combining two railway network models (Kettner *et al.*, 2003, Sewcyk *et al.*, 2007). The first one, NEMO (Network Evaluation Model), is a macroscopic, strategic simulation model developed since 1999 at the IVE (Institute of Transport, Railway Construction and Operation), in collaboration with the ÖBB (Austrian Railways). It is based on a macroscopic network containing the access point of passengers and freight, and the junctions, intersections, and marshalling yards for freight transport. The demand for passenger transport is described as OD flows per time slice, on the basis of an average day according to the transport. The demand for freight transport is described as flows per commodity group. Both demands are inputs to the model. The transport supply consists, for the passenger transport, of a set of services, delivered by trains of given characteristics operated on given lines and serving given sets of stations. Passengers are assigned on these services. The freight demand is handled in a somewhat different way. Block trains are operated when possible. The residual freight is transported in single wagons, which follow routes between marshalling yards, according to a given routing protocol. Optimal empty wagons flows are computed using the DISPO software, also developed by IVE, to address potential imbalances. Apart from the block trains, all services are determined i.e. specified as exogenous. The demand, both freight and passengers, is assigned on this set of services. The volume of trains required on each line is then determined, so as to meet the demand on the most heavily loaded section between two neighbouring stations. The number of trains required for each service is endogenous. As a result, the model is able to predict the network load due to freight and passenger transport. NEMO allows one to analyze these outputs, for example by evaluating the economic efficiency of the infrastructure.

RailSys is a microscopic operational simulation model, developed since the 1980s by IVE, mainly for the German Federal Railways. In RailSys, the infrastructure is represented as a highly detailed network, taking into account physical characteristics (radiuses, gradients, etc.), the signalling system (overlaps, release contacts, etc.), and the operation process (prioritisation strategies and railway operation process). A detailed database is thus necessary for the functioning of RailSys. RailSys then calculates, with respect to the trains characteristics, the running times and minimum headways, using a point mass system and the potential safety running time margins. Using all these data, and a defined train operation, RailSys simulates timetables describing accurately the movements of all trains.

NEMO and RailSys have been interfaced respectively as client and server. The first reason for integration is that it allows both models to rely on a unique database, which ensures that they share consistent data. The second reason is that the outputs of the NEMO model are based on extremely accurate data. The model integration proceeds as follows: firstly, the microscopic network representation of the infrastructure in RailSys is used to automatically generate a macroscopic network in NEMO (*Figure*

1). RailSys also transfers the timetables, from which NEMO defines available services and the number of trains for each service. Then, NEMO compares the demand to the supply. If there are more trains than needed, the superfluous trains are removed. On the contrary, if the demand exceeds the supply, then NEMO sends RailSys a request to add a train in the timetable. RailSys then searches for an additional train path. Passenger trains are processed first, then the additional freight trains. It may be impossible to find a path. Finally, capacity limitations may be investigated. We will not get into the detail of this evaluation, which consists roughly in determining the ratio of time during which the infrastructure is occupied. A high ratio indicates a potential bottleneck.

The interface built between NEMO and Railway has two main advantages. First, it allows the use of already existing, accurate data, thus saving the cost of further data collection, and providing a representation of the infrastructure based on highly realistic data. The representation of capacity problems is all the more accurate (although the capacity limitation identification criterion may be discussed). Second, it is very interesting to note that this architecture allows to measure quantitatively, at a strategic, macroscopic level, the impact of a change in operating modes (such as the signalisation, speed limits, or priority rules).



**Figure 1: Automatic conversion of the microscopic railway network in RailSys into the macroscopic railway network in NEMO (Kettner et al. 2003).**

## 2.2 The formation of scale economies.

Scale economies are one of the main drivers of the organisation of freight transport, and, on a larger scale, of companies' logistic choices. They characterise a production process such that the unit cost of the product is decreased when the quantity produced is increased. Such a situation is frequent in freight transport under at least two forms: first, decreasing unit cost with the loaded volume (e.g. due to the fixed capacity of the vehicles, or the presence of fixed assets – logistics platforms, railways, etc.); second, decreasing unit cost when the frequency is increased (e.g. due to lower detention costs). Scale economies are of particular importance in large organisations, such as hub and spoke networks, or non-road modes. However, their formation is seldom explicitly represented in freight transport models, especially when it comes to service frequency; this is quite an issue for both efficient supply design and policy

assessment, since economies of scale are externalities and thus have a particular implication for regulation.

In the model of Groothedde (2003), scale economies are represented in an explicit way on the basis of the frequency and size of shipments, together with demand grouping by the transport supplier. The model is applied to the design of a profitable, reliable, inland waterway freight transport network, in the highly demanding field of palletized fast moving consumer goods (FCMG). As explained by Groothedde, a number of companies tried to set up such an organisation for their own use, but all of them failed. The project *Feasibility of Inland Shipping Networks: "Distrivaart"* was aimed at developing an intermodal hub network that would comply with the requirements of FCMG transport. Groothedde's work showed that scale economies could be achieved to make the network a profitable enterprise.

The proposed transport scheme consists in a set of inland waterway services whose frequency is determined (a service being defined by an itinerary and a set of served ports), provided by dedicated pallet barges with capacity of about 20 truckloads. These services are organised in a hub and spoke pattern. Each freight shipper makes the decision to have its shipment carried on by either the truck only, or the waterway service, which necessitates specific truck movements and transshipment operations (Figure 2). As the transport time by waterway usually exceeds the order lead-time, demand has to be anticipated before it is sent by waterway. This is only possible up to a certain point, and the residual demand has to be accommodated by direct road transport.

An extensive market analysis was performed to identify the potential market. Manufacturers and retailers were identified, yielding a market of 26.6M pallets a year. The search of the optimal set of services was tackled as an optimisation problem, consisting in the minimisation of total costs (including operating costs, detention costs, and handling costs.) Note that some costs were not considered, notably the potential costs of the cooperation between agents pertaining e.g. to the harmonisation of time-windows between manufacturers. Once defined, the problem was solved using the simulated annealing method, which provided both an optimal organisation, and a development path, made up of stages of increasing profitability.

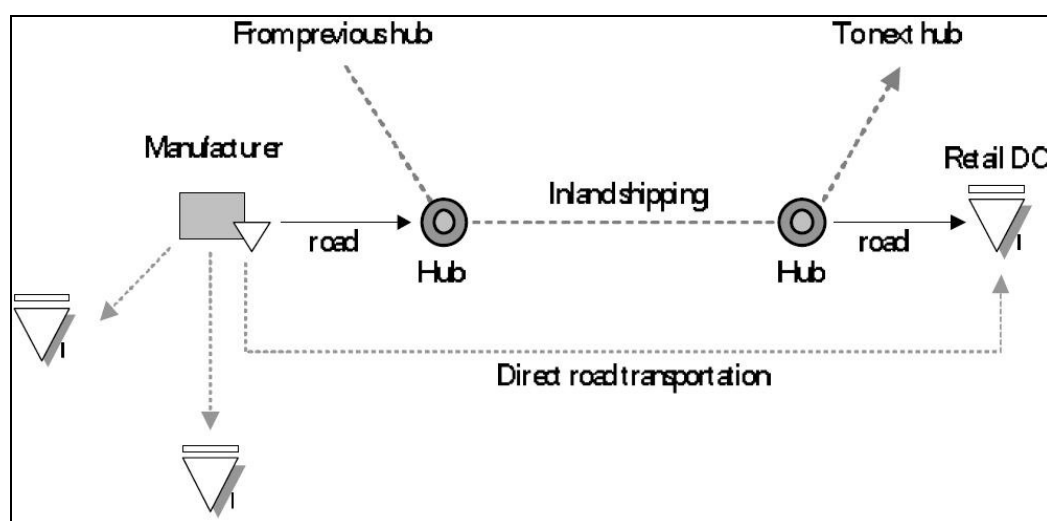


Figure 2: The transport possibilities (Groothedde, 2003).

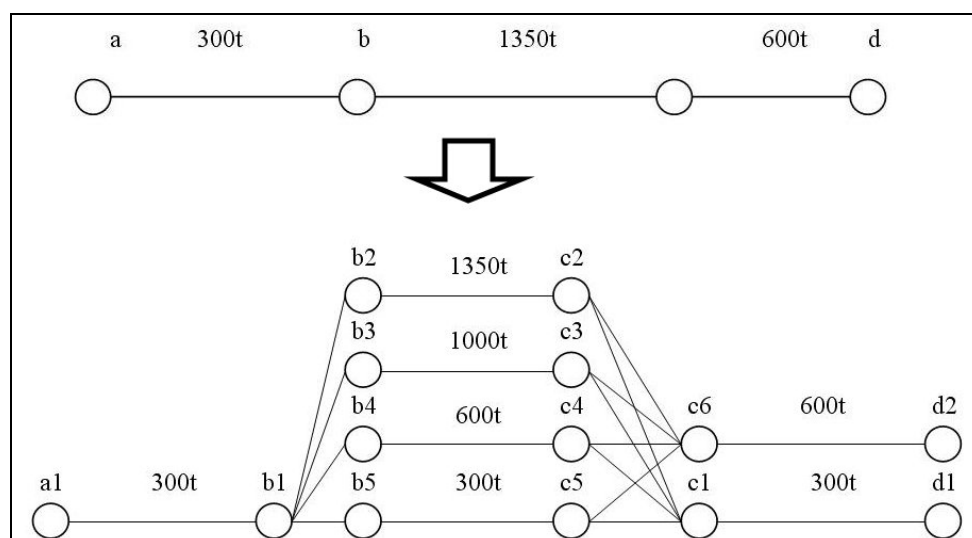
This methodology may be hard to extend to the scale of macroscopic simulation, due to the high amount of data and computation demanded. Nevertheless, it can be applied to design intermodal transport services in an operational context: if it is successful to yield profitability on a financial account, then its potential for social welfare is obvious since it also provides gains in environmental pollution and congestion. To sum up, Groothedde's work exemplifies scale economies achieved by the transport supplied due to the cooperation between demand agents.

### 2.3 Integrating logistic features in transport chain and generalised cost.

The choice of the transport mode for freight demand is in general modelled as the minimisation of the shipment generalized cost provided by each mode. This is evaluated by taking into account the physical attributes of the mode path such as carriage time, money cost, need for handling, reliability, etc... In addition the generalized costs may be cast into the framework of random utility and discrete choice models, in which the principle of utility maximization yields a choice probability for each alternative.

Owing to model calibration, the method may prove efficient even when the drivers of mode choice are not thoroughly understood – which is certainly the case when logistic features are neglected, or when the contract terms between the shipper and the transport supplier are specific.

The NODUS model has been designed by Jourquin, Beuthe *et al* (2000, 2002, 2005) to cope for the first flaw, by way of refined representation of the features along the transport chain for each shipment from origin to destination, including logistic operations. In NODUS both the logistic and transport operations are modelled as transitions from state to state, a state being characterized by location and type of conditioning. A transition induces a change in location and/or conditioning, together with a time expense plus a money cost which depend on the logistic or transport technique utilized. The transport techniques are distinguished by infrastructure type and vehicle type e.g. several types of barges. The network of states and transitions makes up the supply network in NODUS (*Figure 3*); hence a network path from origin state to destination state models a transport chain including logistic operations.



**Figure 3: Formation of the supply network in NODUS, on the basis of the infrastructure network (Jourquin & Beuthe, 2000).**

Precisely, the transition attributes associated with a network arc induce a generalized cost which accounts for the following items:

- movement costs implied by physical operations (capital cost, labour, fuel, insurance, maintenance, tariffs), be it on board or during a loading, unloading, or transshipment operation.
- inventory costs implied by the detention of goods (opportunity cost, potential depreciation cost) and the storage costs.
- residual costs (like general administrative costs).

These costs should depend on the shipper and shipment type of size. This is approximated by distinguishing commodity groups. Costs are evaluated on the basis of a unit cost per ton, which implies that the shipment size is not taken into account. Costs pertaining to information availability, reliability or freight safety are not taken into account.

The network paths from an origin to a destination thus represent alternative transport chains that may make use of all available modes, eventually in sequential combinations i.e. intermodality. Each shipment flow is faced with a set of transport chains, and it is assigned to the chain with minimal generalized cost. Congestion effects can also be modelled at the arc level.

To sum up, the NODUS approach enables one to represent explicitly the various drivers in the generalised cost of carrying a shipment through a logistic and transport chain. In connection to the search for scale economies, the approach is suitable to predict the demand choices between barges of different capacities.

## 2.4 Modelling the spatial and technical structure of the industry.

The demand for freight transport arises from the fact that the demand and supply of commodities are spatialised and temporalised. A description of the commodity demand and supply therefore provides a strong basis for the generation of freight transport demand, especially its linkage to the rest of the economy, which can be particularly relevant in a forecasting objective.

Out of several methods that have been developed to model the demand for freight transport, let us focus here on the Spatialised Input-Output (SIO) models, which capture both the spatial and economic relationships between the local demand and supply of commodities. The IO feature is that, in a given industry sector, the production of a given level of output necessitates to consume related levels of inputs coming from various industry sectors. The technical relationships make up the sector production structure; since the original model of Leontief (1936) they are generally modelled as linear combinations, of which the coefficients are known as *technical coefficients*.

In an SIO model, the spatial structure is also addressed by distinguishing regions of production – hence of intermediary consumption. This requires to model:

- the production structure by industry sector and region.
- The trade between regions for each type of input i.e. each commodity group. This trade gives rise to the freight flows between regions. It may be modelled by trade coefficients which indicate, by output sector and region and by sector of input, the split of its demand for input between the regions of production. In turn the trade coefficients may be modelled on the basis of either economic principles such as utility maximization (taking into account both the input



price in the production region and the transport cost from production to consumption region), or of statistical principles such as inference by entropy maximization.

The last issue in an SIO model pertains to the final consumption by region and sector. This makes a specific model input which, together with the industry intermediary consumption, sets the need for, and level of, economic production.

The paper by Marzano and Papola (2004) provides an overview of SIO models and other model families.

## 2.5 Identifying the logistic stages within the trade relationship.

A model of production and consumption may be coupled with a model like NODUS so as to integrate the logistic and transport costs within the trade relationships between regions. However such a treatment would miss issues of scale economies in logistics, notably those related to warehouses. Indeed a warehouse, through the storage of one or several commodities, is purported to facilitate the matching of disaggregate demands and supplies over time and/or space.

The identification of warehouses and maybe also other logistic places e.g. break-bulk platforms along logistic chains from production to consumption region necessitates a specific model. Let us now introduce two methods designed to tackle this issue.

The first approach has been designed in the frame of the SCENES European project (ME&P, 2002). This project had a number of objectives, among which building a European spatialized transport model, by improving the STREAMS model (ME&P, 2000). The SCENES model includes an SIO freight transport demand model, which yields PC matrices by commodity group. The PC to OD issue is addressed by a specific logistical module called SLAM (Spatial Logistics Appended Module), which works in three stages as follows:

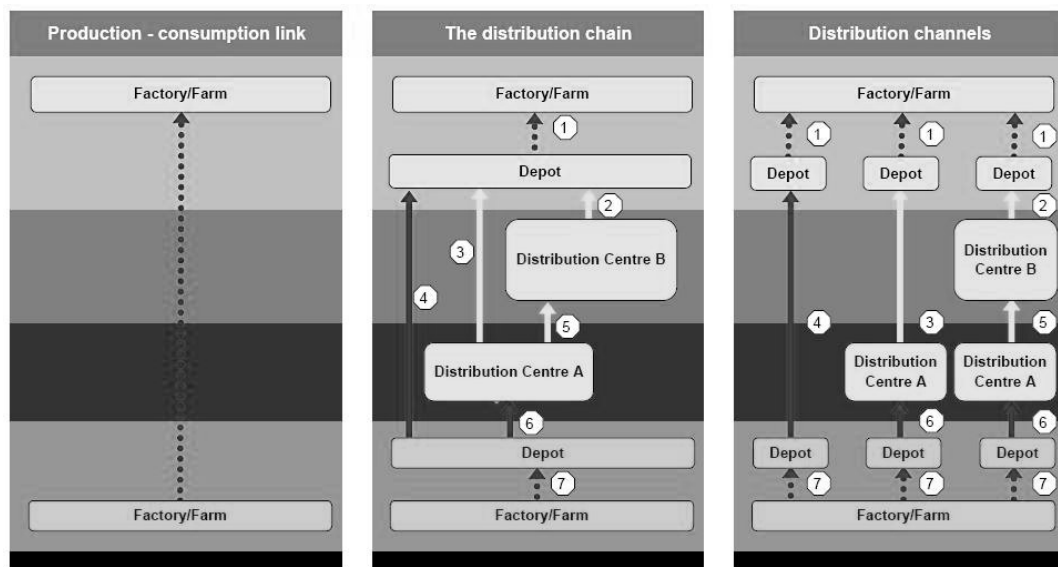
- First, by PC pair a small set of regions with distribution centres is generated. The selection of the set is based on three factors, respectively of economic activity, centrality (representing the presence of the region in the flows for the PC pair), and accessibility to the various infrastructures networks.
- Then, a number of candidate logistic chains are generated, whereby the commodity travels through zero, one or two of the previously selected distribution centres. The generalised cost of each kind of chain is evaluated on the basis of transport costs (the arc cost being a weighted average of the costs of the various modes), inventory costs (uncertainty of the demand, safety), and logistics costs (detention, handling).
- Finally, the PC volume is assigned to the candidate chains according to a nested logit model, where the logistic chain type is determined at the upper level, then its geographic location at the lower level.

The model yields OD matrices between zones of production, consumption or logistic stage. These include the usage of logistic facilities by freight flows, and the amount of usage at a given place is related to the amount of logistic facilities supplied there.

The second approach, taken in the EUNET2.0 model (Jin & Williams 2005), is also based on a SIO model of production and trade, in association to a model of logistic chains that represents high-level logistic stages. However the two features are embedded in a single, extended SIO framework, wherein significant logistic stages are addressed as additional industry sectors.

In the EUNET model, by commodity group a set of candidate logistic chains is defined (*Figure 4*). Each chain consists in a series of transitions called *logistic legs* such as factory towards depot, or distribution center towards local wholesale. Commodities are therefore also distinguished by the logistic leg they comply with, consequently making up what we could call *virtual commodity groups*. The trade between regions is assumed to derive from a utility maximisation behaviour, taking into account the generalised transport cost and the scale factors that characterize the regions' industrial and logistic structure. As a consequence, the productions, consumptions, exchanges between regions and logistic chains are simultaneously calculated. Some logistic specific variables which could be observed, like the handling factor (*i.e.* the number of time the freight is touched between the production and the consumption places), are used for model calibration. In EUNET the PC matrix integrates the logistic stages, which need not to be modelled in an companion logistic module such as SLAM.

The approaches in SCENES and EUNET both take into account the logistic organisation as determinant of freight transport demand. Their application requires a reasonable amount of data, neglecting the details of the logistic choices made by the various companies. A common, major advantage is to address mode choice in the context of the choice of an integrated transport and logistic chain. However, some economic hypotheses in the IO models are questionable (particularly the linearity of the interdependence between the sectors, and the non-substitutability of production factors). Furthermore the logistic choices are not modelled in a micro-economic, behavioural way, which puts at risk any forecasting application.



**Figure 4: An example of logistic chain in EUNET (Jin & Williams 2005).**

## 2.6 Modelling the carrier behaviour.

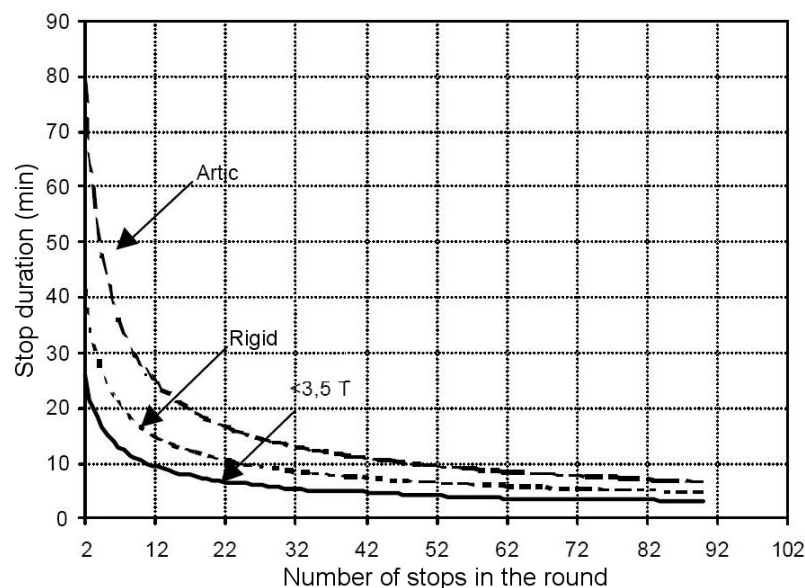
Urban freight transport is a particular problem since its characteristic features of specific shipment endpoints, small distances, small commercial speeds, small shipment sizes and need to organize efficient rounds make it difficult to comply with the classical four-stage architecture of demand models. The FRETURB model of Routhier, Ambrosini *et al.* (2002, 2004), developed in the frame of the French research program TMV (*Transport de Marchandises en Ville i.e.* Urban Freight Transport) is aimed to analyze freight flows in an urban area on the basis of limited

data requirement; a related objective is to assist local authorities in their transport policy.

Within the TMV program, three large surveys were conducted in the French cities of Lyons, Toulouse and Dijon: strong statistical regularities were identified concerning, first, the organization of truck rounds in terms of stop number and duration and average distance between two stops (*Figure 5*) etc; second, the infrastructure impact of urban freight transport in terms of parking type and duration, of road traffic due to trucks etc. These regularities were imbedded in FRETURB to model the commercial vehicles' movements on a given urban area on the basis of a set of socio-economic variables.

FRETURB's architecture is original in two ways. First, as a spatialized model it is focused on a set of zones that represent the area under study, rather than a network of nodes and arcs.. As a consequence the model does not yield indicators by nodes and arcs, but indicators aggregated by zone: total distance covered (in vehicle.km), road occupancy (in vehicle.hours distinguished by the type of occupancy: moving, parking, illegal parking, etc.) Second, FRETURB has a specific architecture which combines the following modules:

- Movements' generation: in each zone, the number of movements (delivery and pickup operations) is estimated from the number and characteristics of the economic activities within the zone described by the type of activity, the type of settlement (offices, warehouse, etc.), the number of employees, etc.
- Calculation of the distance covered by the commercial vehicles: knowing the number of movements, the way rounds are organised, and a number of descriptive variables such as the zone's density, the distance covered by the commercial vehicles between each operation is predicted, and as a consequence the total distance covered is estimated.
- Road occupancy calculation: this is performed along similar principles.
- Road occupancy with respect to time of day: this is computed on the basis of observed timetables.



**Figure 5: Average duration of a stop with respect to number of stops in round and to vehicle type (Routhier et al., 2002).**

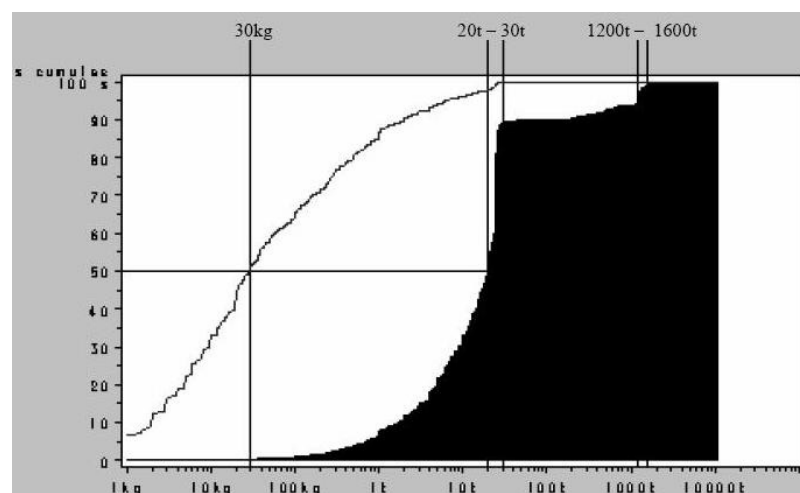
To sum up, the FRETURB model is an elaborate way to extrapolate results of surveys conducted in a limited set of cities to any city of similar socio-economic development by using a limited amount of descriptive data. It is all the more relevant as urban freight transport is a particularly difficult context to address by classical demand modelling methods, both for theoretical (companies behaviour, organisation of rounds) and practical reasons (need for data). However, policy testing possibilities are limited with this model for at least two reasons. First, the framework is not suited to cost-benefit analysis. Second, as the model replicates the observed behaviour of transporters' self-organisation, it is not able to predict how they would adapt to change in the economic environment, which arises when a policy is implemented.

## 2.7 Shipment survey.

Among the issues that are not addressed in the modelling methodologies reviewed so far, let us quote those of shipment size, and of the cooperation between the various agents involved in a transport chain. Both issues are particularly relevant in the context of an individual freight carrier: however no generic theory at the macroscopic level is available yet; even if it were, its application would require critical data about shipments. A shipment survey is appropriate to yield such data and to provide insight into then behaviour of both shippers and carriers. Let us now introduce the ECHO survey, which was conducted in France from 2002 to 2004, of which the first results have been made available by Guilbault *et al* (2007).

The ECHO survey is based on a sample of about 3,000 businesses and 10,000 shipments (a shipment being defined as a given amount of freight of a given kind, made available at given place and time, by a unique shipper in order to be moved as a whole towards a given, unique recipient). Shipments using non-road modes were over-sampled to improve statistical significance. Each shipment was accurately described, with particular emphasis on the relationships between the various agents involved in the shipment transport chain. The shipper business was also described, with emphasis on the way it organises its production.

This survey already yielded noticeable results about the structure of shipments and the use of transport modes within transport chains. It can certainly be used for much deeper analyses, notably concerning the shipment size and the relationships between freight agents.



**Figure 6: cumulative distribution of shipments, in nb / volume (Guilbault, 2007).**

## 2.8 Identifying the long-run drivers of freight transport demand.

Beside the spatial structure of freight transport demand, the long-run drivers in its temporal evolution make a major issue in the understanding of the transport system. In the last decades, in-depth changes have taken place pertaining to the logistic organization of firms, the organisation of transport (optimisation, subcontracting), the inventory strategy (including mutualisation and concentration), the production organization (outsourcing, specialisation, postponement), market strategies (product diversification, short order lead-times, short life-cycles), etc. (e.g. see Dornier & Fender, 2007). In parallel, the sector of freight transport and logistic has been consolidated, which also implies specialisation, externalisation, merges. All these evolutions impact the freight supply and demand, and therefore vehicle flows, and it is a tempting issue to identify the causalities and put them in a hierarchy.

The European project REDEFINE was conducted in the 4<sup>th</sup> Framework Program to analyze the logistic drivers of the transportation demand in five countries (France, Germany, the Netherlands, Sweden and the United Kingdom), using both quantitative and qualitative approaches. The quantitative approach, in which we are interested, consisted in relating the overall industrial production, expressed in monetary unit, to the overall distance covered by commercial vehicles throughout a series of stages characterized by key ratios.

The set of key ratios provides a framework for the distinction and analysis of the various trends in the evolution of freight transport demand. These are listed hereafter:

- Value density: the ratio of the value of a produced good to its mass is useful to convert a production expressed in monetary units into tons, the mass unit for freight transport.
- Modal split: the proportion of goods mass which is carried by the road.
- Handling factor: the ratio between the mass lifted and mass produced. This ratio stands for the average number of times the goods are touched.
- Average length of haul.
- Vehicle carrying capacity.
- Load factor: this ratio defines the average filling rate of the vehicles.
- Empty return: to yield the share of those vehicles running empty.

| Breakdown                             | France | Germany | Netherlands | Sweden | United Kingdom |
|---------------------------------------|--------|---------|-------------|--------|----------------|
| Value of production and imports       | +28%   | +14%    | +17%        | +82%   | -4%            |
| <i>Value density</i>                  | +23%   | -2%     | -3%         | +51%   | -32%           |
| Weight of produced and imported goods | +4%    | +16%    | +21%        | +21%   | -7%            |
| <i>Modal split</i>                    | +10%   | +20%    | 0%          | +11%   | +1%            |
| Products transported by road          | +14%   | +33%    | +21%        | +34%   | +1%            |
| <i>Handling factor</i>                | +2%    | -2%     | +3%         | -20%   | +18%           |
| Road tonnes-lifted                    | +16%   | +31%    | +25%        | +8%    | +18%           |
| <i>Average length of haul</i>         | +36%   | +4%     | +29%        | +37%   | +24%           |
| Tonne-kilometres                      | +57%   | +33%    | +60%        | +48%   | +46%           |
| <i>Vehicle carrying capacity</i>      | +15%   | N.A.    | +24%        | +28%   | +9%            |
| <i>Load factor</i>                    | +7%    | N.A.    | -3%         | -4%    | -4%            |
| Average payload                       | +23%   | N.A.    | +20%        | +22%   | +4%            |
| <i>Empty running</i>                  | -21%   | N.A.    | -7%         | -7%    | -5%            |
| Vehicle-kilometres                    | +28%   | N.A.    | +30%        | +18%   | +37%           |

*Italic cells are ratios, others are aggregates.*

**Table 1: Changes in economic activity and road freight transport 1985-1995 (NEI 1999)**

Using this analysis framework, an overall trend may be broken into a set of simpler phenomena (*Table 1*). As a consequence, it is possible to identify the critical determinants and, up to a certain point, the scope for policy. It is also possible to use this framework for extrapolation. The main disadvantage of the approach is that the key ratios are still very aggregate indicators. Their respective trends may well hide widely varied evolutions at the disaggregate level of microeconomic agents. Thus the REDEFINE model provides a first step towards understanding the system evolution, rather than a definitive explanation.

### 3. ASSESSMENT.

Having reviewed some advanced models for freight transport demand, we are now in a position to assess their respective outreach with respect to the following set of issues: first, the demand model in terms of volume, behaviour and heterogeneity; then, the supply model in terms of networks and services; next, the relationships between agents and the market externalities; lastly, the potential outreach for policy assessment.

Our criteria are targeted mainly to supply-demand models, wherein the demand and supply are modelled separately prior to being faced with each other, which yields the activity of the related sector in freight transport. Out of the models reviewed, those in REDEFINE and, up to a certain point, FRETURB, are focused on freight transport activity in a straightforward way.

#### 3.1 Quality of the demand's representation.

The demand for freight transport derives from the need in given places of commodities available elsewhere. Given the transport services available and their characteristics, shipments will be transported in order to fulfil this need. The main questions from a modelling perspective are: how to quantify the need for transport? On which grounds and in which way are the transport services selected? To which extent can the shipments be aggregated in the model?

#### 311 Demand volume.

On the basis of much empirical evidence (e.g. Guilbaut *et al*, 2007), shipments are known to be widely varied in size and characteristics. Besides, few freight databases include such a level of detail. As a consequence, the demand for freight transport is often stated in flows of a given intensity, expressed in tons per period of time, from origin to destination zones, by type of commodity. Overall, the demand is generally represented by a set of matrices.

Network assignment models focus on how the transport demand, taken as an input, results in vehicle flows on the infrastructure networks. This category includes NODUS and NEMO. In such a model, a set of OD matrices is taken as input in the model, and, in any forecasting application, the analyst has to make assumptions about the matrices evolution over the period of interest.

Other models are targeted to the formation of freight transport demand: notably those in the SCENES and EUNET research projects, which both include an SIO component. They proceed jointly to the generation and the distribution of the freight transport demand. This architecture enables to derive the need for freight transport from the spatial and industrial structure in the area of scope. Here the two recent achievements

are, first, the description of the industrial structure hence the population of shippers taken in an aggregate way; second, the inclusion of important logistic stages related to warehouses and platforms, into the process of production and distribution. Thus the Production-Consumption matrices, as yielded by the SIO model, are turned into origin-destination matrices, which are more appropriate for the choice of transport services.

We outlined the strategy used in the SCENES model, which consists in appending a specific module (SLAM), in order to turn the P-C matrices into O-D matrices. Such a module can be designated as an *LIO stage*, for Logistic Input-Output. The EUNET approach takes a different way: logistic organisations were categorized and commodity groups were further disaggregated to distinguish the *logistic leg* that pertains to the commodity. Both approaches allow for logistic imperatives to appear in the formation of freight transport demand, although the drivers in the logistic choices are not modelled in a microeconomic way.

Among the models we reviewed, FRETURB is the closest to considering shipments explicitly. The demand is predicted on the basis of variables describing the economic and industrial base of the area of scope. Furthermore, it is not expressed in flow but in operations (pickup or delivery). Shipments are not considered explicitly, but the level of detail is high, and the demand formation is closely linked to the industrial basis, which is very appealing in a forecasting perspective.

To sum up, the demand for freight transport differs from the demand for passenger transport at least for its specific linkage to the rest of the economy. The projects of making explicit the logistic imperatives and of taking the shipments as the decision unit have been undertaken, but the recent advances still leave much room for development.

### **312     Description of the demand transport behaviour.**

When the transport demand is available to the modeller, the next step is to predict which transport services will be used, *i.e.* how the freight flows will spread on the networks. Along a partition which has already been proposed (see e.g. Marzano & Papola 2004), we distinguished two main strategies used in the works reviewed. The first is mainly statistical: a set of descriptive variables are used to predict the flows, using a number of statistic regularities. The second approach is based on the description of the agents' behaviour, including notably the paradigm of utility maximisation.

#### **312a     Statistic approach.**

The statistic approach is best illustrated in FRETURB wherein, from the large amount of data collected in a sample of three cities, a number of statistic regularities were observed about the derivation of freight transport from industrial and economic activity. Thus econometric relationships were estimated to link the intensity of freight transport to variables describing the industrial and economic basis. The way shippers and transporters organise themselves is not considered.

The SLAM module in the SCENES model is also based on a statistic approach. In order to turn P-C flows into O-D flows, the module yields the probabilities for a break-bulk operation and the region where it would take place. Three indicators of

economic activity, centrality and infrastructure accessibility are used as explanatory variables, with no underlying economic model.

Both approaches are readily operational and yield useful results; either one may be instrumental in a forecasting perspective but, as will be shown later, they are not so much appropriate for policy testing.

### **312b Behavioural approach.**

In a behavioural approach, some agents are explicitly modelled as decision-makers involved in a choice process to select one from among a set of alternatives. In most of the models that we reviewed, the network route between two places of origin and destination for a shipment is modelled as a discrete choice, of which the decision-maker may be the shipper or a carrier. No indication is provided to distinguish between the two economic positions; in the real world they are indeed integrated in the case of own account transport.

Then comes the issue of which choice alternatives may be considered by the decision-maker. In the area of freight transport the significant advance is to identify alternatives that integrate transport and logistic features: this is achieved in the NODUS model with the identification of logistic operations along the transport chain.

The next step in a behavioural approach is to model the perception and evaluation of the choice alternatives by the decision-maker. In conjunction with the identification of logistic features in the transport chain, the significant advance here is to identify the economic drivers of the logistic behaviour, including operation costs, detention costs, inventory costs and handling costs: this is also achieved in the NODUS model <sup>(2)</sup>. A related advance is to take into account the temporal requirement on the shipment: this is achieved in Groothedde's model with the segmentation of shipments with respect to the requirement of disposal either with some delay or as soon as possible.

The last issue in the behavioural approach pertains to the economic preferences of the decision-maker, and to his trade-off between the attributes of an alternative. The classical method is to evaluate each alternative on the basis of a generalized cost (or disutility function), which takes into account every attribute eventually weighted by a coefficient of trade-off against money. Here the advance would be to make two separate accounts of, respectively, the time and money expenses: thus a time versus cost trade-off could be modelled at the level of the integrated alternative; and the decision-makers could be distinguished by their relative preference of time to cost (i.e. their unit value of time). This approach has two main advantages: first, in terms of economic outreach, this enables to model non linearity in the utility functions and also to make explicit the influence of the agent's money budget as well as that of his time budget; second, it is instrumental in that this increases the modeller's control over the calibration process and provides more flexibility in the specification of a statistical distribution for agents' trade-offs between time and money. This advance has been achieved in passenger mode choice models since the 1960s, especially in price-time models (Quandt, 1968; Marche, 1973). However in the freight models that we reviewed the time and cost expenses are not accounted for separately at the level of the choice alternative. To our knowledge the distinction is only achieved in the truck network assignment of the French Department for transport (Danzanvilliers *et*

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<sup>2</sup> the approach is restricted to facilities that are available to any customer, with no distinction of firm



al, 2005), thus being restricted to route choice on a road network by O-D pair with no consideration of logistic features.

An additional issue pertains to the shipment size. Obviously the choice of the shipment size depends on the commodity group and its logistic requirements, the distance to overcome, and also the available transport services and their characteristics (e.g. Hall, 1985). This issue is particularly relevant to understand well the freight transport activity and how to regulate it.

### **313     Addressing demand heterogeneity.**

The demand consists in a set of agents (or a set of shipments sent by or routed by these agents), who need to use a transport service. These agents or flows may however have very different requirements on those services, and considering them as a uniform population may lead to large biases in freight transport modelling.

There are two classical strategies to tackle demand heterogeneity. The first one is to split the demand into classes (also called segments), which is very much constrained by the level of detail in the available data. Flows are generally classified by commodity group (as in almost all the works reviewed in this paper), but some groups may still be very heterogeneous. The segmentation in EUNET is noteworthy since the commodities are distinguished by logistic family. Demand segmentation is purported to improve the model relevance by grouping the similar components of demand; however there is the issue of which criterion would be relevant to characterize this similarity. The notion of a logistic family is still to be defined clearly; if some commodity groups had similar logistic imperatives, their transportation would probably be organised in similar fashions, which would be amenable to a unified model. Demand segmentation has been taken in an original way in FRETURB, in which the businesses are distinguished along a number of characteristics.

A related strategy, which was not used in the models we reviewed, consists in modelling the drivers of demand heterogeneity in a probabilistic way, by associating a random variable with given statistical distribution to each driver and also a joint distribution to the vector of drivers. This is an explicit, probabilistic approach to demand heterogeneity – in fact very much the same as demand segmentation into classes.

The second broad strategy is to address demand heterogeneity in an implicit way, in the framework of random utility theory, by incorporating an error term in the utility functions that the agents associate to choice alternatives, as in the logit choice model. This error term stands for unobserved characteristics or idiosyncratic choice criteria, among other features (e.g. Ben-Akiva and Lerman, 1985, Anderson *et al.*, 1992.) This is instrumental when the drivers of some choices are not fully understood, particularly so in the case of the modal choice. This strategy is used in SLAM and EUNET.

The two strategies are integrated in the framework of discrete choice models, by making the random utility functions to depend on the segment characteristics (such as in random utility with random coefficients).

## **3.2     On the supply representation.**

Let us come to the supply-side and consider it in a demand-oriented perspective: our aim is to assess the supply features that are relevant in the demand behaviour and

choices. The detailed models of supply operations fall out of our scope, except in their connections to the demand, as in the interaction of Railsys and NEMO.

Let us consider in turn the three issues of, respectively, the spatial and layered representation of supply; the modelling of transport and logistic features; and the formation of scale economies.

### **321    On the spatial and layered representation of supply.**

Throughout our review except for ECHO and REDEFINE, the spatial extension of the supply is modelled, either in a zone-based approach in the case of FRETURB, or in a network-based approach. A network model of nodes and arcs is most appropriate for the infrastructure layer, be the transport mode the road, the railway, the inland waterway, maritime or air.

In connection to the infrastructure layer, two other layers may be modelled. The distinction of vehicle types is achieved in NODUS. The distinction of both vehicle types and services is achieved in NEMO about the railway mode, and in Groothedde's model about the road and inland waterway modes.

However there is yet no model of integrated transport and logistic operations as delivered by some logistic providers in the real world: this is related to the issue of making explicit the shipment size, which was pointed to in § 3.1.2.

### **322    The modelling of transport and logistic features.**

Nevertheless, significant advances have been achieved to model logistic features and operations within a transport chain: in NODUS these are modelled by dedicated network arcs, whereas in SLAM and EUNET the significant logistic stages are made explicit and used to turn PC relationships into OD relationships.

### **323    On macroscopic relationships : scale economies and congestion.**

Scale economies are of particular importance at every layer in the supply of freight transport, then also in the transport and logistic choices of the demand: in the shipment size, shipment frequency, vehicle and mode choice, and service choice. The classical way to represent scale economies in models of freight transport demand is based on a mass unitary cost associated to any operation of a transport or logistic kind, together with transition costs associated to any transfer from one operational stage within the transport chain to the next. This approach enables to simulate how the demand agents can profit by the scale economies; it provides no indication of the formation of scale economies, of the underlying rationale of the transport and logistic providers. To achieve that purpose, a refined model of supply is in order, as in Groothedde's work. An intermediary step is taken in NODUS, in which the unit costs are related to the characteristics of the facility.

Another macroscopic relationship between the flow intensity and the level of service is that of congestion. This issue has been much more observed and well understood than the formation of scale economies, and it is often modelled on the basis of a speed-flow relationship at the level of a given transport arc. This requires to define a flowing capacity for that arc: models of roadway capacity have been well-developed, whereas the capacity of non-road modes is a more complex issue that must be addressed at several layers (in terms of vehicles, shipments, services...). The impact

of congestion on reliability is also a topic for further research, for road and non-road modes.

### **3.3 On the relationships between the agents and market externalities.**

#### **331 On the relationships between sector agents.**

The formation of scale economies is closely related to the industrial organization of transport supply, hence to the relationships between the transport and logistic providers. Another such relationship lies in the complementariness of the various facilities and services, which can be used in an integrated way by the demand agents. No other feature of supply relationship was detected in our review.

On the demand side, in every model it is assumed that shipments are independent of each other: little attention is paid to the issue of the shipment size, which pertains to the internal organization of the demand agent and is obviously more important than any relationship between demand agents. A noticeable exception to that point is the real-world context of Groothedde's work, where shippers joined together so as to stimulate the design of a multi-client service: in our classification this is rather an issue of scale economy.

Lastly, the matching between providers and users was indicated in the French shipment survey, ECHO: this provides some insight into the commercial relationships in the freight transport sector, especially about the temporal requirement and the price.

#### **332 On market externalities.**

The macroscopic relationships of scale economies and congestion constitute market imperfections (or distortions) in the framework of the neoclassical theory of microeconomics.

Other market imperfections lie in the external impacts that the freight system exerts on the socio-economy and the environment: these include positive impacts such as the achievement of scale economies in any sector of the economy, as well as negative impacts – from the emission of pollutants and noise, to the risks of accidents and the degradation of the residents' living conditions. These external impacts fall outside the topic of freight demand models: it is easy to address the negative impacts by using dedicated models by impact type, taking the flow and level of service results of the demand model as input to evaluate the impact.

### **3.4 On the ability to assess regulation policies.**

This is a twofold issue: first, can a modelling framework accommodate the implementation of a given policy? Second, is it possible to perform a Cost Benefit Analysis, and what would be its outreach?

To answer these questions requires to compare the policy targets and instruments with the scope of the model in terms of (1) supply representation, so as to effectively accommodate the implementation of the policy; and (2) demand representation, so as to effectively simulate the demand response to the policy. From our earlier observations, it is obvious that the NODUS, SLAM and EUNET models provide the widest frameworks for policy assessment. The FRETURB model may be appropriate to simulate some of the effects of a change in commercial speed in an urban setting.

If the model is policy-responsive, then it may be used to perform a CBA of the policy under investigation.

#### 4. CONCLUSION.

##### 4.1 Synthesis based on a two-dimensional typology.

In this paper, advances in freight transport demand models were reviewed and assessed. Let us sum up our analysis by putting forward a classification framework, in which each model is assessed along the two dimensions of the focus and the behavioural content.

The focus axis includes three categories as follows:

- Supply side orientation: this indicates advances in the representation of transport and logistic features.
- Demand side orientation: this indicates advances in the formation of the demand and/or choices of the demand agents.
- Sector activity orientation: the focus is on deriving the intensity of the freight transport sector activity, in a direct way rather than through a demand-supply model.

The behavioural axis includes three levels of analysis, presented hereafter by order of increasing depth and outreach (<sup>3</sup>):

- Descriptive approach: this pertains to the works that provide more data, or some trend analysis, without further treatment. Such works provide a sound basis for further studies and, up to a certain point, the understanding to freight transport.
- Statistical method: this category refers to works in which statistic regularities are identified between various variables, but with no underlying microeconomic model.
- Behavioural method: this pertains to explicit models of agent behaviour, often on the basis of utility maximisation. This category is most appropriate for realistic simulation, project evaluation and policy assessment.

| Approach<br>Orientation |                   |             |                                     |
|-------------------------|-------------------|-------------|-------------------------------------|
|                         | Descriptive       | Statistical | Behavioural                         |
| Supply side             |                   |             | NEMO-RailSys<br>Groothedde<br>NODUS |
| Demand side             |                   | SLAM        | EUNET                               |
| Sector activity         | ECHO,<br>REDEFINE | FRETURB     |                                     |

**Table 2: Modelling advances typified by focus and behavioural content.**

<sup>3</sup> This typology axis was suggested in other researchs (e.g. Catalani, 2003).

## 4.2 Some research perspectives.

Our typology provides insight into how to combine the recently-achieved modelling advances, so as to take an in-depth approach to several topics from among demand, supply and activity, and/or to improve the behavioural content.

As the field of freight transport makes indeed a large area for study and research, several directions for development were suggested along our review. Let us emphasize here two issues which we believe particularly relevant for further investigation:

- Market structure: the relationships between the various agents of a transport chain, and particularly the contracts they link, certainly exert a strong influence on the elaboration of transport services and costs, and therefore on the shippers' decisions. For instance, large flows may imply strong competition on some links and some modes, low prices, and as a consequence, high availability and flexibility for the shippers. Conversely, scale economies are achieved through capital-intensive techniques, meaning that some cooperation between suppliers is required to harvest their advantage – which probably requires in turn some coordination mechanism. Overall, the market structure plays an important role in freight transport, particularly so in the intensity of demand and its modal choices.
- The choice of the shipment type: the size, frequency, conditioning of the shipments result from demand decisions made under the supply conditions? In the theory of logistics, there are models for the choice of shipment size and frequency; they still have to be incorporated into the demand-side of freight transport demand models.

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